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Navy Experimental Diving Unit

DEPARTMENT OF THE NAVY
NAVY EXPERIMENTAL DIVING UNIT
Panama City, Florida 32407

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NAVY EXPERIMENTAL DIVING UNIT
REPORT NO. 11-80

TESTING OF DECOMPRESSION ALGORITHMS FOR USE IN THE U. S. NAVY UNDERWATER DECOMPRESSION COMPUTER

PHASE I

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Methods for programming a wrist worn Underwater Decompression Computer (UDC) were investigated and tested. All testing was done on the MK-15 UBA which supplies a constant P_{O_2} of 0.7 ATA in N_2. Testing was done submerged in water temperatures of 73-78°F and with dive subjects performing moderate exercise. A total of 445 man-dives were conducted to depths of 175 FSW, and a total of 22 cases of decompression sickness occurred. A total of 5 methods for computing decompression profiles were investigated and of these one was

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selected as being the most suitable for programming the UDC. The method chosen would not decompress divers safely from all profiles so it's use was restricted to a maximum time of 30 min at 150 FSW. This restriction was integrated into the program so the UDC could warn the diver if he were exceeding permissible limits at any depth. A total of 178 man-dives were done within the restriction placed on the UDC with only 2 cases of decompression sickness observed. A series of non-repetitive diving tables using the selected method was also produced to permit safely diving the MK 15 UBA without a UDC.

This report was initially distributed to a limited number of people and was entitled, "Preliminary Report, Testing of Decompression Algorithms For Use in The U.S. Navy Underwater Decompression Computer". Since its distribution, the report has been referenced several times so it was decided to officially promulgate it in the present form. Further testing of algorithms for use in the decompression computer will constitute separate reports.

ABSTRACT

Methods for programming a wrist worn Underwater Decompression Computer (UDC) were investigated and tested. All testing was done on the MK-15 UBA which supplies a constant P_{O_2} of 0.7 ATA in N_2. Testing was done submerged in water temperatures of 73 - 78°F and with dive subjects performing moderate exercise. A total of 445 man-dives were conducted to depths of 175 FSW, and a total of 22 cases of decompression sickness occurred. A total of 5 methods for computing decompression profiles were investigated and of these one was selected as being the most suitable for programming the UDC. The method chosen would not decompress divers safely from all profiles so it's use was restricted to a maximum time of 30 min at 150 FSW. This restriction was integrated into the program so the UDC could warn the diver if he were exceeding permissible limits at any depth. A total of 178 man-dives were done within the restriction placed on the UDC with only 2 cases of decompression sickness observed. A series of non-repetitive diving tables using the selected method was also produced to permit safely diving the MK 15 UBA without a UDC.

Introduction:

The U.S. Navy Underwater Decompression Computer (UDC) is a small wrist-worn microprocessor capable of monitoring both depth and time and using this information to compute decompression profiles. The UDC was developed specifically for the Special Warfare Community by the Naval Ocean Systems Center (NOSC) in Hawaii to be used as part of the Swimmer Life Support System (SLSS) package. The SLSS package consists of the Underwater Decompression Computer (UDC), the MK-15 Mod-0 Underwater Breathing Apparatus (MK-15 UBA), and a Full Face Mask (FFM).

The mission of Special Warfare divers requires that they perform long duration, multiple depth dives, making the use of conventional diving tables impractical. Recent advances in microprocessor and depth transducer technology had made it possible to build a small, easily carried decompression computer and NOSC Hawaii was contracted to build a prototype for evaluation. The Navy Experimental Diving Unit was tasked with evaluating various algorithms for computing decompression profiles and to perform man-testing to decide which profiles were safe. The initial requirements for developing the UDC were that it compute safe decompression profiles to depths of 175 FSW using a breathing gas with a constant 0.7 ATA of O_2 in N_2.

Furthermore, the UDC had to perform satisfactorily over a mission profile of 6 hours which was the operational limit of the MK-15 UBA component of the SLSS package.

The UDC gives the free swimming diver ultimate flexibility by constantly updating his decompression requirements thus providing the diver with a decompression schedule ideally suited to his particular depth/time profile. It performs this function by monitoring diver depth every 2 seconds and using a algorithm to compute a safe ascent depth (SAD). The SAD is displayed concurrently with the diver's actual depth so that at any instant in time the diver knows exactly what his actual depth is and to what depth he could safely ascend. Upon reaching the SAD, the diver waits until the SAD decreases thus allowing him to safely ascend to the next shallower stop. Thus, by continuously matching his depth to the SAD, the diver will eventually decompress to the surface. Once on the surface, as long as the UDC remains turned on, it will continue to update his decompression status so that when he enters the water for a repetitive dive, the UDC will take into account all previous dives in computing the new decompression schedule.

Thus, assuming the proper algorithm is used, the UDC can safely guide the free swimming diver through the most intricate depth/time profile no matter how many excursions or surface intervals are included.

This report describes the results of some 445 man dives performed at the Navy Experimental Diving Unit in evaluating various methods of computing decompression schedules for use in the UDC. Recommendations as to which method should be used and any restrictions placed upon its use are also included.

Methods:

All of the experimental dives were conducted using Navy and Army divers as subjects. All divers were given a complete diving physical before participating in the study, and were examined before and after each dive by a Diving Medical Officer. Each diver was thoroughly trained on the dive protocol. Divers were grouped into 2 teams of 12 to 15 for each study, 10 divers being selected from a given team for each dive. The dive schedule was arranged so that every diver had a minimum of 36 hours between dives. After surfacing from a dive, divers were required to remain at the chamber facility for 2 hours and then to be within 30 minutes of the chamber facility for the next 4 hours. The chamber facility was kept in standby for treatment for a full 24 hours after any dive.

Two dive series were successfully conducted, the first consisting of 197 man-dives, the second consisting of 208 man-dives. All dives were done in the wet chamber of the Ocean Simulation Facility of the Navy Experimental Diving Unit, with all divers kept in the water for the entire dive. Water temperature was kept between 73-80°F and all divers wore standard 3/8" neoprene wetsuits consisting of "farmer john" trousers, jacket, hood, gloves and boots. The water temperature was selected to chill the divers to just the point of being uncomfortable without causing dive aborts. All the divers

breathed from a MK-15 Mod 0 closed-circuit UBA set to deliver a constant partial pressure of 0.7 ATA O_2 in nitrogen. With the MK 15 set to deliver .7 ATA O_2, the actual P_{O_2} of the breathing gas varies between 0.6-0.8 ATA O_2. The divers were usually breathing from the MK-15 UBA for the entire dive but occasionally the divers would have to exit the wet pot and come off their UBA's and breathe chamber atmosphere for short periods due to a UBA malfunction. Chamber atmosphere was always air; therefore any occasion where the diver breathed chamber atmosphere was kept as short as possible so his decompression obligation did not significantly differ from that of his fellow divers.

The first series of 197 man-dives were performed using pre-printed profiles generated by a Hewlett Packard HP-21 MX Computer. The HP-21 MX was programmed to generate decompression profiles using exactly the same algorithm as used by the UDC. Several problems were encountered in accurately following pre-printed profiles since there was typically several holds of up to 10 minutes duration during descent because of ear squeezes which could not be anticipated during profile generation. During the second series of dives,

the HP-21MX Computer continuously monitored chamber depth from an Ascroft Digigauge and updated the divers decompression status every 2 seconds. Thus, any holds or deviations from the planned dive profile were taken into account in computing the decompression profile. The diver's depth and SAD were continuously displayed on a CRT computer display at the chamber control console and diver depth was matched to the displayed SAD during decompression. Dive profiles were recorded by the computer such that after a dive both the diver depth and SAD could be plotted by a digital incremental plotter.

All divers were always decompressed on exactly the same schedule and when in the wetpot were approximately 10 FSW deeper than the chamber depth. The divers entered the wetpot one at a time at the start of the dive, approximately 5 minutes elapsing from the time the first diver entered the water until the last diver entered the water. When all divers were in the water, they swam down to the 10 FSW depth and after a 5 minute equipment checkout the chamber and wetpot were compressed. Since the HP-21MX Computer was programmed to add 10 FSW to the chamber depth to calculate diver depth, as soon as the computer program was started it assumed the diver depth was 10 FSW. The computer program was started when the first diver entered the water and during the initial 5 minute period which it took all divers to enter the water, the computer was calculating the diver's decompression schedule as if they were at 10 FSW.

Independent calculation indicated that this 10 foot discrepancy in depth at the beginning of the dive could last up to 10 minutes without significantly affecting the decompression profiles for the dives used in this study.

The algorithm for computing decompression profiles is essentially that of Braithwaite (1) which was based on Workman's method (7). Nine halftime compartments with halftimes ranging from 5 to 240 minutes are used. Gas uptake and elimination from these compartments is described by the formula:

$$(1)\quad P_{new} = P_{IN} + (P_{old} - P_{IN}) \times 0.5^{(T/T_{1/2})}$$

P_{new} = Compartment inert gas partial pressure at the end of time interval T.

P_{old} = Compartment inert gas partial pressure at the start of time interval T

P_{IN} = Ambient inert gas partial pressure at the beginning of time interval T

$T_{1/2}$ = Compartment halftime

T = Time Interval

The ambient inert gas partial pressure (P_{IN}) is calculated from the formula:

$$(2)\quad P_{IN} = P_A - P_{O_2}$$

P_A = Absolute ambient hydrostatic pressure

P_{O_2} = Partial pressure of oxygen in the breathing gas

All pressures used in the calculation were in feet of seawater (FSW) with 33 FSW being equal to 1 ATA. Thus, for the MK-15 UBA with a constant PO_2 of 0.7 ATA, the PO_2 used in the calculation would be:

$$0.7 \text{ ATA} \times 33 \frac{\text{FSW}}{\text{ATA}} = 23.1 \text{ FSW of } O_2$$

The decompression computer updates the compartment gas tensions every 2 seconds therefore the time interval in equation (1) is:

$$T = \frac{1}{30} \text{ Min}$$

If depth is changing, then P_A in equation (2) will not be constant over the time interval T. In the evaluation of equation 1, the UDC uses the P_A which exists at the beginning of time interval T. With ascent and descent rates of up to 75 FPM, making the time interval T shorter than 2 seconds does not significantly increase the accuracy of equation 1, thus the 2 second time interval is felt to produce a very small error in calculations made during ascent and descent.

When a diver is using the UDC, there will be occasions where he may be at the surface breathing air for various periods of time. The P_{N_2} of air is 26 FSW of N_2 which is quite different from the 10 FSW of N_2 present in the breathing gas of the MK-15 UBA when the PO_2 is 0.7 ATA. In order to provide for surface intervals breathing air, the UDC is programmed so that whenever the diver depth is less than 3 FSW, the PO_2 in equation 2 will be assumed to be .21 ATA (7 FSW of O_2) which will make the P_{N_2} 26 FSW of N_2. If the diver should breathe from his MK-15 UBA while at the surface, he will not get into any problems since the PO_2 in the breathing gas of the UBA is higher than that being assumed by the UDC. Once the diver descends below 3 FSW, the PO_2 in equation 2 is again 0.7 ATA.

Decompression was regulated by table of "M-values". An M-value is the maximum permissible compartment inert gas tension at any depth. In computing the SAD, the UDC compares the inert gas tensions in each of the 9 compartments to their M-values and picks the shallowest depth at which all compartment gas tensions are less than or equal to their respective M-values.

The M-values were computed in 10 FSW increments, thus the SAD is always in 10 FSW increments, which means that the stops during decompression are in 10 FSW increments.

It was anticipated that during the course of the study, the method of computing decompression profiles might have to be changed should it become evident that a particular set of profiles were unsafe. This was done in all cases but one by changing the M-value table. Four sets of M-values were used in the course of this evaluation, these are listed in Appendix 1. Decompression calculation modifications designated as Mod-1, Mod-2, Mod-3, and Mod-5 used the respective M-values as shown in Table 1 and used a P_{O_2} of 23.1 FSW of O_2 (0.7 ATA) in equation 2. The decompression calculation modification designated as Mod 4, used MVAL 3 as the M-value table but used a value of 19.8 FSW of O_2 (0.6 ATA) in equation 2. In all of the decompression calculation modifications, the same algorithm was used to compute the decompression profiles.

There were eventually 12 different dive profiles tested using the UDC program. These are shown in Table 2. These profiles were chosen because they represented cross sections of worst-case profiles for the particular depth used. In addition, since the SLSS would be used for multiple repetitive dives, several multiple repetitive dives were included in the series. These profiles were 5 to 6 hours long, which is the practical

TABLE 1

M-VALUES AND P_{O_2}'s USED IN THE VARIOUS DECOMPRESSION CALCULATION MODIFICATIONS

Decompression Calculation Modification	M-Value Table Used	P_{O_2} In Equation 2 (ATA)
Mod-1	MVAL 1	0.7
Mod-2	MVAL 2	0.7
Mod-3	MVAL 3	0.7
Mod-4	MVAL 3	0.6
Mod-5	MVAL 5	0.7

TABLE 2

TEST DIVE PROFILES

Profile	Depth/Time Combinations
1*	175/30 → 10/60 → 175/30
2	175/60
3*	150/30 → 30/120 → 150/30
4*	125/30 → 10/30 → 125/30 → 10/30 → 125/30
5*	75/30 → 10/15 → 75/30 → 10/15 → 75/30 → 10/15 → 75/30 → 10/15 → 75/30
6	150/60
7	150/45
8	100/60
9	150/30
A	100/45
B*	150/30 → 10/90 → 150/30
C	75/120

All number pairs are Depth (FSW)/Time (Min)

Times indicate actual time at the indicated depth and do not include descent time, or decompression time.

The last decompression was always to the surface.

* On multiple depth dives in going from a deeper depth to a shallower depth, any required decompression stops were taken. Thus, the total ascent time depended on the Decompression Calculation Modification being used (see Appendix 2).

duration of the gas supply in the MK-15 Mod 0 UBA component of the SLSS. During the testing of the dive profiles, 2 subjects at a time exercised on underwater bicycle ergometers for periods of 10 - 20 minutes at work rates of 25-50 watts, after which two new subjects took their turn on the ergometers. This rotation continued throughout the entire dive profile so that all subjects were exercised approximately the same amount. The 25-50 watt work load was estimated from previous exercise studies to produce oxygen consumptions of 0.8 - 1.25 l/min.

Ascent and descent rates used in this study were dictated by the limitations of the chamber complex. Descent was 20 FPM and ascent 30 FPM to a diver depth of 30 FSW, 15 FPM from 30 - 20 FSW, and 5 FPM from 20 - 10 FSW. Divers surfaced by swimming from their 10 FSW depth in the wetpot to the surface of the wetpot at approximately 75 FPM.

Results:

The results of the 445 man-dives eventually completed are shown in Table 3. The broken line separates the dives of the first series where pre-printed profiles were followed from the second series where on-line computer generated profiles were followed. All cases of DCS are noted in the table. The letters key the cases of DCS with the descriptions in Appendix 3. All cases of DCS were successfully treated with no discernable residual effects. Decompression calculation Mod-1 was abandoned after 3 pain only decompression sickness (DCS) occurred on profile 2. Profile 1 had two cases of pain only DCS but this dive was felt not to be a true test of decompression calculation Mod-1 since the two divers who acquired DCS had to breathe air during the latter stages of decompression because of a UBA malfunction. Mod-2 proved safe on profiles 3 - 6 but on the deep profiles 1 and 2, two central nervous system (CNS) DCS occurred forcing abandonment of MVAL 2. Mod-3 proved very safe in its initial testing phase indicating the MVAL 3 would generate safe profiles. Unfortunately, after 97 dives without a single case of DCS, the next 30 dives produced 4 cases of pain only DCS. In 3 cases, the divers who got DCS had been diving repeatedly during the previous several weeks of the study and it was felt that this sudden increase in incidence of DCS might have been due to diver fatigue. For

TABLE 3

TEST DIVE RESULTS

PROFILE	**1 (175/30)*2 10/60	2 175/60	3 (150/30)*2 30/120	4 *3 (125/30) 10/30*2	5 (75/30)*5 (10/15)*4	6 150/60	7 150/45	8 100/60	9 150/30	A 100/45	B (150/30)*2 10/90	C 75/120
Mod 1	8/2(1)[a]	10/2(1) /1(2)[b*]										
Mod 2	10 9/1(2)[c]	9 {1(1)[d] 1(2)[e]}	8	10	7	9						
Mod 3	6 9 10		9 10 10/1(1)[f*]	9 8 10/1(1)[g]	9 9	9 9 10/2(1)[h]				Dive Series 1 May - June 1977		
			10	10/1(1)[j]		10/2(1)[k]				Dive Series 2 Feb - Mar 1978		
Mod 4						10/1(1)[l]						
Mod 5			# 9 10 9	# 10 10 10 10	# 10 10 10	10 10 {2(1)[q] 1(3)[r]}	10/3(1)[m]	# 10/1(2)[n]	# 10 10	# 10 10	# 10/1(2)[p]	# 10 10

* All 10 subjects treated

\# Dives used in computing DCS incidence for Mod-5 restricted (see text).

** For profile abbreviation convention, see Appendix 2.

Number pairs represent NUMBER OF SUBJECTS/DCS (Type of DCS). Single numbers represent the number of subjects on DCS free dives.

DCS Types: 1 - Pain Only
2 - CNS
3 - Cardiovascular

Letters key DCS with descriptions in Appendix 3.

this reason Dive Series 1 was concluded and a new crew of dive subjects recruited for Dive Series 2. During this second dive series, one team of divers dove only on Mondays and Thursdays and the second team only on Tuesdays and Fridays. This gave a minimum of 60 hours between dives which was adequate to prevent diver fatigue and preclude any possibility of inadequate decompression between dives. Of the initial 30 man-dives of Dive Series 2 using MVAL 3, three cases of pain only DCS occurred and it was felt that this incidence of DCS was unacceptable. Ten man-dives were done using decompression calculation Mod-4 and dive profile 6 with one case of pain only DCS. Since profile 6 was so much longer using Mod-4 than Mod-3 (Appendix 2) it was felt that just dropping the PO_2 used in calculating P_{IN} from 0.7 ATA to 0.6 ATA was not going to produce safe tables so MVAL 5 was calculated. The basis for calculating MVAL 5 were:

(1) All M-values the same for any compartment at a given depth

(2) Total decompression time equal to but not less than Mod 3 for profiles 3, 4, 5, 6

(3) Decompression stops deeper than in Mod-3 profiles.

As can be seen in Appendix 2, these goals were met in all cases cxcept for profile 6 where Mod-5 produced a decompression profile about 3.5 min shorter than Mod-3. This small difference was felt to be insignificant and it was thought that the deeper stops would compensate.

Profiles 1 and 2 were not to be included in the testing of Mod-5 unless all other profiles proved safe. Therefore, the fact that profile 2 had a shorter decompression time using Mod-5 than Mod-3 did not dissuade from testing Mod-5. Should profile 2 have eventually been tested and proven unsafe, it could have been lengthened in its deeper stops without affecting the shallower profiles.

The results of the testing of Mod-5 using MVAL 5 are shown in Table 3. Profiles 3, 4, and 5 produced no DCS in 98 man-dives. Profile 6 however produced 3 cases of DCS in 20 man-dives, one case being serious with cardiovascular symptoms which responded to treatment with no residual effects. Failure to get safe dives on profile 6 with any of the decompression calculation modifications led to the abandonment of the 60 minute bottom interval at 150 FSW and search for the maximum safe bottom time at this depth. Three pain only bends on the 150/45 schedule (Profile 7) led to a 150/30 schedule (Profile 9) which produced 20 DCS free man-dives. Having determined that 30 min was a safe bottom interval at 150 FSW, it was decided not to test profiles any deeper than 150 FSW but to try a variety of new profiles shallower than 150 FSW to gain as much data as possible in the depth range of 75-150 FSW during the remaining time allocated for the study. The first goal was to determine the maximum safe bottom intervals at 100 and 75 FSW. Profile 8 (100/60) gave 1 case of pain only DCS

in 10 man-dives but the 100/45 profile (Profile A) gave 20 DCS free man-dives. The last dive of the series (Profile B) was similar to profile 3 except that the surface interval was 90 minutes at 10 FSW rather than 120 minutes at 30 FSW. Ten man-dives were done using Profile B with one case of DCS.

From the results, statistical predictions were made regarding the expected incidence of DCS assuming that the occurrence of DCS follows a binomial distribution at a 90% confidence limit. The entire study consisted of 445 man-dives with 22 cases of DCS giving an expected DCS incidence of 6.5%. The numbers of dives done using decompression calculation Mod-1 and Mod-4 are too few to get meaningful statistics. Using Mod-2, three cases of DCS occurred in 62 man-dives giving an expected incidence of 8.5%. When schedules were computed using Mod-3, seven cases of DCS occurred in 157 dives giving an expected incidence of 6.3%. The 208 man-dives done using Mod-5 gave rise to 8 cases of DCS giving an expected DCS incidence of 6.2%.

Discussion:

The Workman method of computing decompression schedules (7) is basically a refinement of the techniques proposed by Dwyer (4, 5) and used by DesGranges (2) in computing the U.S. Navy Standard Air Tables. Braithwaite (1) put the Workman method into a form more suitable for creating computer algorithms. The M-values used to compute the standard air tables were computed from the formula:

$$(3) \quad M = .79 \times 33 \times \left[\left(\frac{S_T}{R}\right)^{10} + R-1\right]$$

M = Maximum permissible inert gas tension at a given depth for a given halftime compartment.

$R = M/P_A$

P_A = Absolute ambient pressure

S_T = Empirically derived surfacing ratio for compartment with halftime T

It should be noted that this formula is totally empirical and is not derived from any physiological considerations. To find the M-values for a given halftime compartment, the value for the surfacing ratio S_T and ambient pressure P_A are put in equation 3 and the equation solved for M by standard iterative techniques. The M-values used by DesGrange to compute the Standard Air Tables appear in Table D of Appendix E of NEDU Report 6-65 (7). Unfortunately, if one uses these M-values to compute the Standard Air Tables, not all of the resultant tables

agree with those published in the U.S. Navy Diving Manual. The reason for this is that non-systematic modifications were made to certain tables after initial computation. MVAL 1 was computed using equation 3 by adjusting the 9 surfacing ratios so that when a set of air tables were computed using these M-values they were a very close approximation to the Standard Air Tables. Where differences between the computed tables and the Standard Air Tables occurred, the computed tables always had longer total decompression times and deeper stops. Having a method which would accurately compute the Standard Air Tables, it was felt that safe constant 0_2 partial pressure tables for N_2-0_2 could be computed by merely using equation 2 to compute the inert gas tension instead of the equation used in computing air tables which is:

$$(4) \quad P_{IN} = P_A * F_{N_2}$$

P_{IN} = inert gas tension

P_A = absolute ambient pressure

F_{N_2} = fraction of nitrogen in breathing gas

When Mod-1 was used to compute repetitive dive profiles, the resultant repetitive decompression schedules were much shorter than found using the procedures outlined in the U.S. Navy Diving Manual. The reason for this is that the residual nitrogen times used in determining which

table to use for a repetitive dive assumes that the 120 minute compartment will control decompression (3, 5). Since there was no way of knowing in advance if the repetitive dive procedures in the diving manual were over-conservative, MVAL 3 was computed such that repetitive dive decompression schedules on air were more in line with those obtained from the diving manual. The basis for computing MVAL 3 was a 190 FSW dive for 30 min with a 30 min surface interval followed by another 190/30 dive. MVAL 3 was computed such that the repetitive 190/30 decompression profile computed using Mod-3 was similar to the decompression schedule obtained using the standard repetitive dive procedures (for a 30 min surface interval, the residual nitrogen time would be 26 min, therefore the decompression schedule for the repetitive dive would be the same as a 190/60 table). In doing this, Mod-3 gives a longer decompression profile for the first 190/30 dive than the Standard Air Tables and thus the total decompression time for the two dives is 34 minutes longer than the schedules obtained from the diving manual. MVAL 2 was computed such that the total decompression time for two 190/30 profiles separated by a 30 min surface interval computed using Mod-2 was about the same as that obtained from the diving manual. Equation 3 was used to compute all three sets of M-values by empirically adjusting the 9 surfacing ratios (S_T) until the desired results were obtained.

The results of the Dive Study 1 indicated that both Mod-1 and Mod-2 produced decompression profiles with an unacceptably high incidence of DCS (Table 3). The surprising finding was that the highest DCS incidence for the two sets of M-values were on the single dive profile 2 (175/60), while the repetitive 175/30 profile 1 proved relatively safe.

Based on experience gained from the testing of decompression calculation Mod-1 and Mod-2, it was decided not to test the 175/60 profile until all others proved safe. Mod-3 produced safe decompression schedules for all tested profiles initially, then a rash of DCS occurred on previously safe profiles. One case of DCS was in a diver who was diving in the study for the first time. The other three cases were in divers who had already been subjects on several dives in the study. Although the random nature of DCS occurrence does not preclude cases of DCS occurring together with long periods of DCS-free diving interspersed, Dive Series 1 was concluded at this point so that the data could be analyzed and a further course of action plotted. A total of 12 cases of DCS occurred during Dive Series 1, all cases being of the pain only type except for 2 CNS

symptoms which were both manifested by blurred vision. Both CNS cases occurred after the deep 175 FSW profiles using MVAL 2. Since all cases of DCS using Mod-3 were of the pain only type and since they occurred on consecutive dives, it was felt that Mod-3 should be retested with a fresh crew of divers to rule out some unknown cumulative effect of diving causing increased susceptibility to DCS during Dive Series 1.

The idea that long term cumulative effects caused the DCS which occurred during previous testing of Mod-3 was quickly dispelled when 3 cases of pain only DCS occurred during the first 30 man-dives of Dive Series 2. This discouraging note led us to try increasing the length of the decompression schedules by decreasing the P_{O_2} in equation 2 from .7 ATA to .6 ATA. This would have the effect of lengthening the shallower stops proportionately more than the deep stops. Getting a case of pain only DCS on the first Mod-4 dive caused us again to reconsider the approach we were using to calculate tables. The result of this reconsideration was MVAL 5. MVAL 5 was computed from the following formulas:

for $D \leq 80$ FSW

$$M = 67.46 + D \times (1.157) - (17.46 + 0.157D) \times 0.5^{(D/50)}$$

for $D > 80$ FSW

$$M = 29.59 + 1.035 \times (D+33)$$

where:

D = Depth in FSW

M-values for all halftime compartments were the same at a given depth. The above equations are empirically derived from a graphical analysis of helium-oxygen unlimited duration excursion limits for saturation diving (6) "adjusted" for use with nitrogen. The adjustment consisted of redrawing the graph such that tables computed from the resulting M-values had total decompression time greater than or equal to table computed using MVAL 3 for profiles 3, 4, 5, 6 but with deeper stops. As mentioned in the Results section, the fact that profiles 1 and 2 were shorter than using MVAL 3 was not felt to be important for initial testing since these profiles could be lengthened at a later date without affecting shallower profiles. The testing of Mod-5 using MVAL 5 produced 8 cases of DCS, one of which was a rather serious case involving cardiovascular symptoms. This particular case occurred immediately after the subject exited the chamber after completing a 150/60 dive. The subject appeared pale and complained of lightheadedness. On physical examination he was shivering and had postural hypotension. About 5 minutes after the

initial symptoms the subject complained of severe shoulder pain and at this point was compressed to 60 FSW on O_2. He responded well to compression and after receiving 2-3 liters of Lactated Ringers Solution I.V. his postural hypotension disappeared. Since the time at 60 FSW was 4 hours, the subject and tender were decompressed on a standard Navy saturation decompression schedule. During decompression, the chamber atmosphere was air. After treatment, the subject had no physical signs or symptoms of DCS but did complain of slight malaise which disappeared in a week. The subject had suffered a case of pain only DCS 21 days previously after diving on Profile 6 using Mod-4. He was the only case of DCS on that dive. Two other subjects on this 150/60 dive eventually displayed symptoms of pain only DCS several hours after surfacing. They were successfully treated on Treatment Table 5.

The one severe case of DCS was unnerving since all previous experience with the 150/60 profile gave rise to easily treatable pain only DCS. This dichotomy between DCS symptomatology in subjects on the same dive highlights the large variation in tolerance to decompression which individuals can exhibit. Thus, one must be prepared of the eventuality that previously DCS-free profiles or those which result in only mild DCS symptoms will occasionally produce severe symptoms in certain individuals.

As previously discussed under Results, the 60 minute bottom interval at 150 FSW was abandoned and a safe bottom

interval was sought. Then a safe bottom interval at 100 FSW was found and finally a variety of profiles between 150 and 75 FSW were tried. No profiles shallower than 75 FSW were tried because of time limitations and because the 0% observed incidence of DCS on the 75 FSW profiles (Profile 5, Profile C) using any set of M-values was taken to indicate that these shallow profiles would be fairly safe.

Statistically, there was no differnce in the expected incidence of DCS between Mod-5 and Mod-3 (6.3% vs. 6.2%). This indicates that Mod-3 may be as safe as Mod-5 but restrictions of time prevented the testing of Profiles 8, 9, A, B, and C using Mod-3. Since the object of this testing was to find an operationally useful set of tables and since there appeared to be no distinct advantage of Mod-3 over Mod-5, no further testing of Mod-3 was considered and Mod-5 was chosen as the algorithm for use in the UDC.

Since it was felt that Mod-5 could not be used to decompress divers with an acceptable incidence of DCS from all the profiles tested, and since depths below 150 FSW were not tested, it was necessary to place restrictions on the depth/time durations for dives using Mod-5. The restrictions were set by monitoring the gas tension in

the 40 minute compartment (P_{40}) and warning the diver when the gas tension exceeds some critical value. This warning is implemented by having the SAD display flash when $P_{40} \geq 77$ FSW of N_2. This flashing will continue until the diver decompresses to 30 FSW. Once at 30 FSW, if the diver tries to descend before $P_{40} \leq 48$ FSW of N_2, the warning begins flashing advising him to remain at 30 FSW. It is not until $P_{40} \leq 48$ FSW of N_2 that the diver is allowed to descend again. The limits that this restriction places on initial bottom time and selected repetitive dives for various depths is given in Table 4. The "Max. Initial Bottom Time" in Table 4 is the time at which the warning would turn on after reaching the "Depth of Dive" from the surface. The "Allowable Repetitive Dive Time After Surface Interval" is the time at which the warning would turn on after reaching the "Depth of Dive" after the indicated "surface interval" had been taken. The repetitive dive times in this table are only representative times for all profiles because the actual repetitive time will differ slightly depending on what the previous dive profile was. The times listed in the table are within 2 minutes of the actual times computed for each individual profile.

The underlined depths in Table 4 are the depths used in this study. As can be seen from the "Max. Initial Bottom

TABLE 4

Restricted Mod-5 Profiles

Depth of Dive (FSW)	Max Initial Bottom Time# (Min)	Allowable Repetitive Dive Times# (Min) After "Surface Interval"													
		30 FSW for		20 FSW for			10 FSW for				0 FSW for				
		90 Min	120 Min	60 Min	90 Min	120 Min	30 Min	60 Min	90 Min	120 Min	30 Min	60 Min	90 Min	120 Min	
150	27	15	17	17	19	22	17	22	24	26	19	22	23	24	
140	30	18	20	20	22	24	19	24	27	29	22	24	26	27	
130	33	20	22	22	25	27	23	27	31	33	25	27	30	31	
125	36	22	24	24	26	29	22	29	33	35	26	29	32	33	
120	38	24	26	26	29	32	25	32	35	37	29	32	34	35	
110	44	29	31	31	34	37	30	37	41	44	34	37	40	41	
100	53	35	38	38	41	45	37	45	50	53	41	45	48	50	
90	69	48	50	50	54	59	49	59	64	67	54	59	62	64	
80	90	69	72	72	79	82	71	82	88	92	79	82	86	88	
75	115	90	93	93	99	105	92	105	111	115	99	105	109	111	
70	166	137	142	142	149	155	141	155	162	167	149	155	160	162	
60*	300														
50*	330														
40*	360														

*Dives shallower than 67 FSW will never actuate the warning. The indicated bottom times are those which would result in a total dive time (bottom time plus decompression time) of 360 Min.

#All times represent actual times at depth and do not include descent time.

Times", only single dive profiles 8, 9, A and C (Table 2) would be allowed with Mod-5 restricted. No single dive profile was tested at 125 FSW but it was felt that the safety of the 125/30 repetitive profile (Profile 4) established the safety of a single 36 min bottom time at 125 FSW. To see how the restrictions placed on Mod-5 act during repetitive dives, one need only select the desired "surface interval" to be taken and read the allowable repetitive dive time at a given depth from the appropriate column. Note that the table assumes that all previous dives stayed for the maximum bottom time at a given depth. The restrictions would allow repetitive dive profiles 3, 4, 5, and B to be performed with slight modification. Profile 3 had the diver at 150 FSW for 30 min, decompressed him to 30 FSW where he remained 120 min then had the diver descend to 150 FSW for another 30 min. Table 4 shows that the first bottom interval would be limited to 27 min and that after spending 120 min at 30 FSW, the second bottom interval would be limited to 17 min. Profile 4 had the diver make three 125/30 dives with 10/30 surface intervals interspersed. Table 4 shows that the first 120 FSW dive could have a bottom time of 36 min but that the two repetitive dives made after a 10 FSW "surface interval" for 30 min would be restricted to 22 min. The first 150 FSW excursion in Profile B would be restricted to 27 min while the second

excursion to 150 FSW after a 10/90 "surface interval" would be restricted to 24 min. The restrictions impose no changes in diving Profile 5. Thus, the restrictions insure that all profiles will be well within the bounds of those profiles which were tested.

Several different methods of restricting the dive profiles were tried and the one adopted here gave the best overall fit to the profiles tested which were felt to be safe. Unfortunately, the initial depth requirement of 175 FSW could not be met because there was no time to test profiles deeper than 150 FSW using Mod-5. In order to modify or lift the restrictions further testing would have to be done. Ideally, one would like to do sufficient testing so that only a maximum depth restriction would be necessary for the UDC and that as long as that maximum depth was not exceeded, safe decompression profiles would be computed.

If one now considers only the profiles which fall within the restriction limits placed on the UDC (Table 3) one finds a total of 178 man-dives and 2 cases of DCS giving an expected DCS incidence of 3%. The one case of DCS on the 100/60 profile was initially felt to have CNS involvement in the form of very mild leg parathesia. However, upon reviewing the case, it was felt that at least part of the

symptoms were due to the diver being unusually cold and tired. The restriction placed on the DCS would limit the bottom interval at 100 FSW to 53 min and it was felt that allowing this time at 100 FSW was an acceptable risk. The one case of DCS which occurred on Profile B was attributed to the fact that this diver's MK-15 UBA malfunctioned during the dive letting the diver's inspired P_{O_2} to fall below .6 ATA. By manually adding O_2, the diver was able to just keep his P_{O_2} up to 0.6 ATA. When a decompression profile was generated assuming a P_{O_2} of 0.6 using MVAL 5, it was estimated that this diver had missed about 30 minutes of decompression. After careful analysis, it was concluded that using Mod-5 with the above described restrictions would allow divers to decompress with an acceptably low incidence of DCS.

At a depth of 67 FSW, the P_{N_2} of the inspired gas will be 77 FSW of N_2 and the warning limits will never be exceeded. Thus, at depths of 67 FSW or shallower, dive duration will be limited not by decompression requirements but by the UBA duration as indicated in Table 4. Also, and noted in Appendix 1, the surfacing M-value for all the tissues is 50 FSW of N_2. This means that dives 40 FSW or shallower (the P_{N_2} at 40 FSW is 50 FSW of N_2 if the P_{O_2} is 0.7 ATA) no decompression is required no matter what the bottom time.

In testing any method of decompression profile calculation, limitations of time and money put an absolute limit on the numbers of experimental dives which can be performed before allowing the calculation to be used for operational diving. Statistically, one would have to do 30 man-dives on every conceivable profile with no DCS to establish an expected DCS incidence of 7.4% at the 90% confidence level. Doing more dives would drop the expected incidence but to decrease the expected incidence of DCS on each profile to less than 2% would require 120 bends-free man-dives. The impracticality of testing this exhaustively is obvious. Therefore, some assumptions must be made and some degree of risk assumed. The assumption that must be made is that once a set of maximum safe depth/time limitations are found for a given method of decompression schedule calculation, than all profiles within those limits are safe. That is to say that when one tests dive profiles he is testing the validity of the method of computing the profiles and that all profiles test the validity of the computational method equally. This of course is not exactly the case since experience has shown that the deeper, longer profiles have a higher DCS incidence than shallower profiles. This is where the risk comes in. One must test his computational method under what he feels are a representative

worse-case condition knowing that by not testing all possible depth/time profile combinations, he may be missing a DCS provoking profile. With proper experimental design, however, this risk can be kept acceptably low. It is felt that the testing of the UDC Decompression Program has met these criteria and that tables generated by decompression calculation Mod-5 restricted can be used in operational diving situations. Once used operationally, the large number of dives which will be accumulated on the UDC will provide further validation of Mod-5. Since there will initially be only a small number of UDC's, a very intensive follow-up could be made on all dives to insure all cases of DCS are reported and the causes fully understood. As experience is gained, areas requiring improvement in decompression calculation might become evident and appropriate corrections made.

When one is evaluating a new method of computing decompression profiles, it is natural to compare the incidence of DCS with that of the incidence on U.S. Navy tables. The large numbers of dives done on these tables has established them as the standard to which all others are compared. A review of data supplied by the Navy Safety Center on air dives requiring decompression covering the period January 1971 through December 1977 indicates that 15,311 decompression dives were done with a total of 73 accidents. Mod-5 with

restrictions was tested over a depth range of 75 to 150 FSW which is equivalent to a depth range of 80-170 FSW on air. In this depth range, the Navy Safety Center statistics show 312 dives done with bottom times comparable to the ones used in this study with a total of 2 cases of DCS giving an expected incidence of 1.2% assuming a binomial distribution and a 90% confidence level.

The validity of the above comparisons is highly questionable, however, since the methods of reporting DCS to the Navy Safety Center and the way it was reported in this study are totally different. Dives in this study were all done under worst-case conditions in cold water with the divers performing mild exercise. Depth was accurately monitored and decompression profiles were computed in exactly the same way each time. All cases of DCS were reported so that the actual incidence and the reported incidence of DCS were the same. In contrast to this, dives reported to the Navy Safety Center are done under a variety of conditions from warm to cold water and both at rest and performing exercise. Also, just because a particular table was used does not imply that the diver spent the entire time at that depth. When doing multi-depth dives, standard procedure requires the diver to assume that his total bottom time was spent at his deepest depth for purposes of selecting a decompression schedule. Also, divers are required to select a longer or deeper table

under conditions of cold water or when performing hard work, thus putting him on a longer decompression schedule that would be warranted if time and depth were the only considerations. Finally, there is probably a large gap between the reported incidence of DCS and the actual incidence of DCS. In our study, 7 of 22 cases of DCS occurred more than 5 hours after the dive and many were considered by the divers to be only normal aches and pains. It was only because of intensive coaching by the medical officer to report any ache or pain that these cases were recovered for treatment. Had these cases occurred in a typical operational setting, most would never have been reported and the symptoms would have resolved spontaneously. Thus, direct comparisons probably cannot be made between our study and Navy Safety Center statistics.

The decompression computation modifications in this study do not take into account individual susceptibility to DCS. Our selection of divers was quite random and we had divers who had extensive deep diving experience and others whose diving was confined to shallow depths. There were divers who dove on profiles where DCS was common and never had symptoms of DCS while their fellow diver had only mild pain. We had no way of testing each diver in this study for individual DCS susceptibility but we feel that we had a representative cross section of individuals of varying susceptibility. However, we did not eliminate divers who got pain only DCS from the study. A diver suffering from pain only DCS was given a week off and then

returned to his dive team from which 10 subjects were randomly selected. Thus, we continued to dive the "more susceptible" individuals which means that the resulting decompression calculation method was not biased by removing the "more susceptible" individuals from the study. Notwithstanding, the incidence of DCS using schedules generated by Mod-5 restricted will undoubtedly vary slightly depending on the diver population. To develop a set of decompression schedules which would safely decompress all individuals would be possible but the resulting schedules might be impractically long. It is felt that Mod-5 restricted strikes a good compromise between incidence of DCS and total decompression time.

A comment should be made regarding environmental effects. The low water temperature used in this study was selected to chill the divers but warm enough so that the long duration dives would not have to be aborted because of thermal problems. If diving is done in water colder than used in this study, thermal protection would have to be increased so that divers would not get any more chilled than they were in this study. Should the divers thermal state deteriorate during a dive, it is expected that the DCS incidence will increase. The levels of exercise used in this study were felt representative of the levels of exertion which will be attained by divers using the SLSS package. However, prolonged periods of heavy exertion may increase the incidence of DCS somewhat. Heavy exertion sufficient to cause an increase, however, will probably rarely be encountered.

The level of O_2 in the breathing gas used in this study varied between 0.6 and 0.8 ATA and was assumed to have an average value of 0.7 ATA. By changing the P_{O_2} in equation 2, decompression schedules for various inspired P_{O_2}'s could be computed. The algorithm used in Mod-5 for computing decompression schedules assumes that oxygen plays no role in producing DCS. This is an area of some controversy and debate. If one wanted to breathe a higher P_{O_2} and reprogram the UDC to take advantage of the higher P_{O_2}, the algorithm used in this study might not produce decompressions with the same DCS incidence found in this study. Similarly, if it were necessary to lower the P_{O_2} significantly (i.e., .3-.4 ATA), simply reprogramming the UDC by changing the P_{O_2} in equation 2 may not lengthen decompression adequately. Thus, the algorithm used in this study should not be used for computing schedules where the P_{O_2} in equation 2 was significantly different from 0.7 ATA without further study. It should be noted, however, that a UDC programmed with Mod-5 restricted assuming a P_{O_2} of 0.7 ATA could be used to safely decompress divers breathing a higher P_{O_2} than 0.7 ATA although there is no advantage in doing this.

DECOMPRESSION TABLES

A set of tables computed using Mod-5 restricted is presented in Appendix 4. These tables are for use when

diving N_2-O_2 with a constant P_{O_2} of 0.7 ATA when the UDC is unavailable, such as on training dives. Repetitive diving is not allowed using these tables; the UDC must be used for all repetitive diving. Furthermore, it is recommended that only the UDC or the tables in Appendix 4 be used when diving a UBA which supplies a .7 ATA constant P_{O_2} in N_2 and that equivalent air tables not be used.

Conclusions and Recommendations:

(1) Dive Series 1 and 2 adequately tested the various decompression calculation modifications being considered for use in the UDC.

(2) Decompression calculation Mod-5 restricted will decompress divers with an acceptibly low incidence of DCS.

(3) The UDC be programmed with decompression calculation Mod-5 restricted using MVAL 5.

(4) The UDC be used only with UBA supplying a constant partial pressure of at least 0.7 ATA O_2 in N_2.

(5) Only the tables listed in Appendix 4 be authorized for use when diving UBA's providing a constant P_{O_2} of at least 0.7 ATA in N_2 and their use be limited to non-repetitive dives only when a UDC is not available.

(6) Special procedures be developed for monitoring fleet use of the UDC until a sufficient operational experience is gained.

(7) Lifting or relaxing the restrictions imposed on Mod-5 be done only after additional testing.

(8) Divers be kept as warm as possible when using the UDC.

(9) The feasibility of lock-in to a submarine when decompression is required using a .7 ATM O_2 UBA be demonstrated.

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APPENDIX 1

M-value Tables

The M-values are the maximum inert gas tension which are permissible at the indicated depth.

In computing the Safe Ascent Depth (SAD) the UDC compares the 9 compartment gas tensions with the respective M-values beginning at the current diver depth. It then moves up the rows of the table to find the shallowest depth at which all of the compartment gas tensions are less than or equal to the indicated M-values. Once this row is found, the corresponding depth is then displayed as the SAD. The SAD is updated every 2 seconds.

All M-value units are given in FSW of N_2. (33 FSW = 1 ATA)

Compartment Half-Times are in minutes.

MVAL 1

COMPARTMENT HALF TIMES

DEPTH (FSW)	5	10	20	40	80	120	160	200	240
0	91.245	78.731	67.000	55.790	51.358	49.533	49.272	48.490	46.926
10	110.988	96.416	82.613	69.281	63.967	61.771	61.457	60.515	58.627
20	131.714	114.664	98.482	82.813	76.556	73.968	73.598	72.486	70.260
30	152.485	132.886	114.273	96.233	89.023	86.040	85.613	84.332	81.764
40	173.132	150.977	129.928	109.519	101.358	97.981	97.497	96.046	93.138
50	193.617	168.914	145.439	122.672	113.566	109.798	109.258	107.639	104.394
60	213.936	186.699	160.814	135.704	125.659	121.502	120.907	119.120	115.540
70	234.094	204.339	176.059	148.623	137.647	133.103	132.453	130.501	126.587
80	254.102	221.846	191.186	161.439	149.537	144.611	143.905	141.788	137.545
90	273.969	239.226	206.203	174.160	161.339	156.032	155.272	152.991	148.420
100	293.703	256.490	221.117	186.793	173.059	167.373	166.560	164.116	159.219
110	313.315	273.646	235.937	199.345	184.703	178.642	177.774	175.169	169.948
120	332.811	290.700	250.668	211.821	196.277	189.841	188.920	186.155	180.611
130	352.199	307.658	265.316	224.227	207.784	200.977	200.003	197.078	191.214
140	371.485	324.527	279.887	236.566	219.230	212.054	211.027	207.942	201.760
150	390.675	341.311	294.384	248.843	230.619	223.074	221.994	218.751	212.252
160	409.774	358.016	308.812	261.061	241.952	234.041	232.908	229.508	222.693
170	428.787	374.645	323.175	273.223	253.233	244.957	243.773	240.216	233.087
180	447.719	391.203	337.475	285.333	264.466	255.827	254.590	250.877	243.435

MVAL 2

COMPARTMENT HALF TIMES

DEPTH (FSW)	5	10	20	40	80	120	160	200	240
0	86.031	74.821	64.393	55.790	50.054	48.229	47.969	47.187	45.623
10	104.934	91.831	79.526	69.281	62.399	60.200	59.886	58.942	57.051
20	124.634	109.292	94.857	82.813	74.708	72.116	71.745	70.631	68.400
30	144.348	126.709	110.101	96.233	86.893	83.904	83.476	82.192	79.618
40	163.935	143.992	125.209	109.519	98.947	95.562	95.078	93.624	90.709
50	183.363	161.125	140.176	122.672	110.876	107.099	106.558	104.935	101.682
60	202.630	178.111	155.009	135.704	122.691	118.524	117.928	116.137	112.548
70	221.744	194.957	169.718	148.623	134.403	129.849	129.197	127.240	123.318
80	240.713	211.674	184.310	161.439	146.020	141.082	140.375	138.253	133.999
90	259.548	228.271	198.797	174.160	157.550	152.230	151.469	149.183	144.600
100	278.258	244.756	213.184	186.793	169.000	163.301	162.485	160.036	155.127
110	296.850	261.136	227.480	199.345	180.375	174.300	173.430	170.819	165.585
120	315.332	277.420	241.690	211.821	191.682	185.232	184.309	181.536	175.979
130	333.712	293.612	255.820	224.227	202.925	196.102	195.125	192.193	186.314
140	351.995	309.718	269.875	236.566	214.107	206.913	205.883	202.791	196.594
150	370.186	325.744	283.859	248.843	225.232	217.669	216.587	213.336	206.821
160	388.292	341.694	297.776	261.061	236.304	228.374	227.239	223.831	216.999
170	406.315	357.571	311.630	273.223	247.325	239.030	237.842	234.277	227.130
180	424.262	373.380	325.424	285.333	258.298	249.639	248.399	244.677	237.217

MVAL 3

COMPARTMENT HALF TIMES

DEPTH (FSW)	5	10	20	40	80	120	160	200	240
0	80.817	70.910	61.786	53.183	48.751	46.926	46.665	45.883	44.319
10	98.855	87.230	76.430	66.158	60.829	58.627	58.312	57.367	55.473
20	117.520	103.899	91.221	79.137	72.857	70.260	69.888	68.772	66.536
30	136.170	120.505	105.916	91.998	84.759	81.764	81.335	80.048	77.468
40	154.689	136.977	120.474	104.725	96.530	93.138	92.653	91.195	88.274
50	173.053	153.301	134.895	117.324	108.179	104.394	103.852	102.225	98.964
60	191.263	169.483	149.184	129.804	119.716	115.540	114.942	113.147	109.549
70	209.326	185.531	163.353	142.176	131.152	126.587	125.934	123.972	120.040
80	227.252	201.455	177.410	154.448	142.494	137.545	136.836	134.709	130.445
90	245.049	217.264	191.364	166.630	153.752	148.420	147.657	145.365	140.771
100	262.727	232.966	205.222	178.726	164.931	159.219	158.401	155.946	151.024
110	280.295	248.568	218.992	190.745	176.038	169.948	169.076	166.458	161.211
120	297.758	264.077	232.679	202.691	187.077	180.611	179.686	176.907	171.335
130	315.123	279.499	246.289	214.570	198.053	191.214	190.235	187.295	181.402
140	332.397	294.840	259.826	226.384	208.971	201.760	200.728	197.628	191.415
150	349.585	310.103	273.295	238.139	219.833	212.252	211.167	207.908	201.376
160	366.691	325.294	286.700	249.838	230.642	222.693	221.556	218.139	211.289
170	383.720	340.416	300.044	261.483	241.402	233.087	231.897	228.322	221.157
180	400.675	355.472	313.330	273.077	252.116	243.435	242.193	238.462	230.982

MVAL 5

COMPARTMENT HALF TIMES

DEPTH (FSW)	5	10	20	40	80	120	160	200	240
0	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000	50.000
10	62.463	62.463	62.463	62.463	62.463	62.463	62.463	62.463	62.463
20	74.988	74.988	74.988	74.988	74.988	74.988	74.988	74.988	74.988
30	87.543	87.543	87.543	87.543	87.543	87.543	87.543	87.543	87.543
40	100.105	100.105	100.105	100.105	100.105	100.105	100.105	100.105	100.105
50	112.655	112.655	112.655	112.655	112.655	112.655	112.655	112.655	112.655
60	125.180	125.180	125.180	125.180	125.180	125.180	125.180	125.180	125.180
70	137.669	137.669	137.669	137.669	137.669	137.669	137.669	137.669	137.669
80	150.117	150.117	150.117	150.117	150.117	150.117	150.117	150.117	150.117
90	156.895	156.895	156.895	156.895	156.895	156.895	156.895	156.895	156.895
100	167.245	167.245	167.245	167.245	167.245	167.245	167.245	167.245	167.245
110	177.595	177.595	177.595	177.595	177.595	177.595	177.595	177.595	177.595
120	187.945	187.945	187.945	187.945	187.945	187.945	187.945	187.945	187.945
130	198.295	198.295	198.295	198.295	198.295	198.295	198.295	198.295	198.295
140	208.645	208.645	208.645	208.645	208.645	208.645	208.645	208.645	208.645
150	218.995	218.995	218.995	218.995	218.995	218.995	218.995	218.995	218.995
160	229.345	229.345	229.345	229.345	229.345	229.345	229.345	229.345	229.345
170	239.695	239.695	239.695	239.695	239.695	239.695	239.695	239.695	239.695

APPENDIX 2

DIVE PROFILE COMPARISON FOR THE VARIOUS DECOMPRESSION CALCULATION MODIFICATIONS

All descents made at 20 FPM

All ascents at:

30 FPM up to 30 FSW

15 FPM from 30 - 20 FSW

5 FPM from 20 - 0 FSW

Indicated times are all min:sec

Not all profiles were tested for each Mod. (See Table 3).

Depth (FSW) and Times (Min) of the profiles are indicated in abbreviated format next to the profile designator. For multiple depth dives, where a particular depth/time combination occurs more than once, the depth and time are in parenthesis and the number of times it occurred indicated by the multiplier outside of the parenthesis. The "surface intervals" between excursions to the deeper depth are indicated by the second depth/time combination. (Also, see Table 2).

Only stops are shown in the profiles; bottom times and bottom depths are not shown. The solid lines on multiple depth profiles indicate the beginning of a repetitive dive.

DIVE PROFILE COMPARISON

Profile 1 (175/30) x2 10/60

MOD Stops (FSW)	1	2	3	4	5
110	---	---	---	---	1:06
100	---	---	---	---	1:40
90	---	---	---	---	1:30
80	---	---	---	---	3:02
70	---	---	---	---	3:14
60	---	---	1:00	1:34	5:38
50	1:34	3:34	4:54	5:44	7:32
40	5:58	6:10	6:22	6:44	8:00
30	11:28	10:02	15:00	16:16	14:32
20	16:26	16:26	14:52	18:34	18:12
10	60:00	60:00	60:00	60:00	60:00
110	---	---	---	---	1:06
100	---	---	---	---	1:34
90	---	---	---	---	1:32
80	---	---	---	---	3:02
70	---	---	---	---	3:12
60	---	---	:56	1:32	5:26
50	1:28	3:28	4:48	5:50	7:32
40	7:00	6:10	8:44	11:40	8:10
30	15:24	14:46	16:04	20:24	17:22
20	27:52	33:38	35:28	46:32	29:50
10	51:44	55:44	79:20	93:12	52:26
TOTAL DIVE TIME:	292:26	303:30	332:20	381:34	349:10

DIVE PROFILE COMPARISON

Profile 2 175/60

Mod Stops (FSW)	1	2	3	4	5
120	---	---	---	---	0:42
110	---	---	---	---	2:32
100	---	---	---	---	2:34
90	---	---	---	---	3:20
80	---	---	:24	1:36	6:22
70	0:56	3:04	5:04	5:18	6:44
60	8:42	6:54	11:10	13:28	8:54
50	13:66	13:16	13:58	15:00	15:24
40	14:14	14:16	14:58	16:04	16:18
30	22:28	28:38	31:48	38:26	24:44
20	35:42	38:10	44:12	53:22	36:58
10	56:30	61:14	76:16	98:50	56:54
TOTAL DIVE TIME	229:35	243:19	275:37	319:51	259:13

DIVE PROFILE COMPARISON

Profile 3 (150/30)x2 30/120

Mod Stops (FSW)	1	2	3	4	5
90	---	---	---	---	0:16
80	---	---	---	---	2:14
70	---	---	---	---	3:14
60	---	---	---	---	3:24
50	---	---	1:04	2:22	6:44
40	3:16	5:12	6:22	6:44	8:00
30	120:00	120:00	120:00	120:00	120:00
90	---	---	---	---	:16
80	---	---	---	---	2:24
70	---	---	---	---	3:14
60	---	---	---	---	3:50
50	---	0:18	2:28	4:06	7:34
40	5:40	6:10	9:04	12:20	8:00
30	15:24	14:44	16:04	23:02	16:44
20	29:20	34:44	38:56	49:30	29:02
10	53:48	60:44	75:15	100:54	51:50
TOTAL DIVE TIME	323:10	337:34	365:38	414:40	362:28

DIVE PROFILE COMPARISON

Profile 4 (125/30) x 3 (10/30) x2

Mod Stops (FSW)	1	2	3	4	5
70	---	---	---	---	0:22
60	---	---	---	---	2:10
50	---	---	---	---	3:36
40	---	---	---	0:06	3:52
30	0:18	1:50	3:50	5:14	8:14
20	6:44	7:10	7:38	9:50	8:48
10	30:00	30:00	30:00	30:00	30:00
70	---	---	---	---	0:22
60	---	---	---	---	2:06
50	---	---	---	---	3:36
40	---	---	---	0:06	4:40
30	2:54	3:32	7:10	10:54	8:32
20	16:26	16:36	17:04	20:26	16:06
10	30:00	30:00	30:00	30:00	30:00
70	---	---	---	---	0:22
60	---	---	---	---	2:04
50	---	---	---	---	3:38
40	---	---	---	0:04	4:20
30	3:10	3:10	7:10	0:40	8:32
20	21:16	26:42	27:36	34:10	16:30
10	47:28	51:14	55:14	74:16	43:36
TOTAL DIVE TIME	285:03	296:01	312:29	352:23	328:13

DIVE PROFILE COMPARISON

Profile 5 (75/30)x 5 (10/15) x 4

Mod Stops (FSW)	1	2	3	4	5
30	---	---	---	---	0:58
20	---	---	---	---	3:54
10	15:00	15:00	15:00	15:00	15:00
30	---	---	---	---	0:58
20	---	---	---	---	4:32
10	15:00	15:00	15:00	15:00	15:00
30	---	---	---	---	0:58
20	---	---	---	4:14	4:54
10	15:00	15:00	15:00	15:00	15:00
30	---	---	---	---	0:58
20	---	---	6:44	3:34	4:54
10	15:00	15:00	15:00	15:00	15:00
30	---	---	---	---	0:58
20	---	---	0:12	5:26	4:54
10	26:30	34:18	45:52	55:14	22:34
TOTAL DIVE TIME	275:37	283:25	286:55	314:35	299:39

DIVE PROFILE COMPARISON

Profile 6 150/60

Mod Stops (FSW)	1	2	3	4	5
90	---	---	---	---	1:12
80	---	---	---	---	3:04
70	---	---	---	---	6:06
60	---	0:44	2:58	4:22	7:06
50	5:58	5:38	9:24	11:40	7:32
40	14:14	14:02	14:56	16:04	15:54
30	15:24	15:24	16:04	20:00	17:22
20	27:52	33:24	36:08	41:08	28:44
10	45:16	49:06	54:10	64:14	43:12
TOTAL DIVE TIME	184:26	194:00	209:22	233:10	205:54

DIVE PROFILE COMPARISON

Profile 7 150/45

Mod	1	2	3	4	5
Stops (FSW)					
90	---	---	---	---	0:30
80	---	---	---	---	3:02
70	---	---	---	---	3:12
60	---	---	---	0:18	6:12
50	0:50	2:50	5:02	6:12	7:32
40	6:12	6:10	8:22	10:36	8:00
30	15:24	14:06	16:04	17:22	16:46
20	16:26	16:46	19:22	25:06	18:10
10	32:54	73:52	40:44	49:20	34:48
TOTAL DIVE TIME	132:56	138:54	150:44	170:04	159:22

DIVE PROFILE COMPARISON

Profile 8   100/60

MOD	1	2	3	4	5
Stops (FSW)					
50	---	---	---	---	2:02
40	---	---	---	---	5:56
30	---	1:42	3:40	6:20	8:32
20	14:28	13:06	16:18	18:34	14:28
10	18:28	23:32	25:20	31:32	18:14
TOTAL DIVE TIME	104:56	110:20	117:18	128:26	121:12

DIVE PROFILE COMPARISON

Profile 9 150/30

MOD	1	2	3	4	5
Stops (FSW)					
90	---	---	---	---	0:10
80	---	---	---	---	1:26
70	---	---	---	---	3:14
60	---	---	---	---	3:24
50	---	---	0:18	0:54	4:30
40	0:46	2:42	4:32	5:24	8:00
30	6:34	6:46	6:56	7:24	8:32
20	13:42	12:20	15:42	18:30	15:48
10	16:36	20:18	22:26	28:08	18:28
TOTAL DIVE TIME	83:48	88:16	96:04	106:30	109:42

DIVE PROFILE COMPARISON

Profile A 100/45

MOD	1	2	3	4	5
Stops (FSW)					
50	---	---	---	---	1:26
40	---	---	---	---	3:52
30	---	---	0:26	2:04	7:28
20	4:26	5:52	8:52	11:20	8:48
10	16:38	15:30	17:14	19:00	17:10
TOTAL DIVE TIME	78:04	78:22	83:32	89:24	95:44

DIVE PROFILE COMPARISON

Profile B (150/30) x 2 10/90

MOD	1	2	3	4	5
Stops (FSW)					
90	---	---	---	---	0:10
80	---	---	---	---	1:26
70	---	---	---	---	3:14
60	---	---	---	---	3:24
50	---	---	0:18	0:54	4:30
40	0:46	2:42	4:32	5:24	8:00
30	6:34	6:46	6:56	7:24	8:32
20	13:42	12:20	15:42	18:30	15:48
10	90:00	90:00	90:00	90:00	90:00
90	---	---	---	---	0:10
80	---	---	---	---	1:22
70	---	---	---	---	3:12
60	---	---	---	---	3:24
50	---	---	0:14	0:52	4:02
40	0:36	2:16	4:08	5:20	8:00
30	6:22	6:46	7:34	10:58	8:32
20	15:54	14:30	17:04	23:26	17:00
10	31:36	40:06	44:56	56:34	31:56
TOTAL DIVE TIME	255:20	265:16	281:14	309:12	302:32

DIVE PROFILE COMPARISON

Profile C 75/120

MOD	1	2	3	4	5
Stops (FSW)					
30	---	---	---	1:46	5:54
20	10:08	10:08	14:54	19:46	16:30
10	29:52	34:46	36:20	47:10	27:06
TOTAL DIVE TIME	169:55	174:49	181:09	198:37	179:25

APPENDIX 3

DECOMPRESSION SICKNESS CASE DESCRIPTIONS

The letters in the first column key the description to Table 3.

DCS Types are:

(1) Pain Only

(2) CNS

(3) Cardiovascular

All cases of DCS were successfully treated on first treatment table unless otherwise noted.

DECOMPRESSION SICKNESS - DIVE SERIES 1
MAY - JUNE 1977

Table 3 Key	Diver Number	Age	MVAL/ Dive	Date	Water Temp °F Start	Water Temp °F Finish	Date Last Dive	DCS Type and Location	Time of Onset Post-dive	Comments
A	1 2	 24	1/1	6 May	78	----	----	(1) R.wrist (1) R.wrist, elbow, knee	1 hr 1 hr	Treatment Table 5. Both divers on air for about 1 hr because of UBA malfunction.
B	3 4 2	24 25 24	1/2	17 May	78	----	----	(1)R.shoulder.knee (1)L&R shoulder (2)Numbness R.wrist. decreased grip strength	30 min 30 min	Treatment Table 5. All 10 dive subjects treated even those without symptoms. Symptoms occurred in spite of being treated with other divers. Treatment Table 5.
E	5	23	2/2	20 May	77	----	17 May	(2)Blurred vision. Tunnel vision	1 hr	Treatment Table 6.
D	6	35					----	(1)[illegible].shoulder	7½ hrs	Required repeat Table 5, 9 hrs after initial treatment on Table 6.
C	7	28	2/1	26 May	77	79	24 May	(2)Blurred vision. L. temporal field	1½ hrs	Symptoms cleared spontaneously 10 min after onset. Treated on Table 6 anyway.
G	8	30	3/4	15 Jun	80	81	13 Jun	(1)L.shoulder	5 hrs	Treatment Table 6.
H	9 10	44 28	3/6	17 Jun	78	----	15 Jun 15 Jun	(1)L.shoulder.arm (1)R.shoulder.elbow	12 hrs 4½ hrs	Treatment Table 6. Treatment Table 5.
F	11	26	3/3	20 Jun	78	----	16 Jun	(1)R.shoulder.elbow	At 30'	Diver got DCS at 30' stop during decompression. All 10 dive subjects treated on Treatment Table 5.

DECOMPRESSION SICKNESS - DIVE SERIES 2
FEB - MAR 1978

Table 3 Key	Diver Number	Age	NVAL/ Dive	Date	Water Temp Start °F	Water Temp Finish °F	Date Last Dive	DCS Type and Location	Time of Onset Post-Dive	Comments
J	12	38	3/4	7 Feb	79	78	---	(1)L.shoulder elbow,both knees	6 hrs	Treatment Table 5.
K	13	23	3/6	9 Feb	77	76	6 Feb	(1)L.shoulder elbow,wrist	1½ hrs	Treatment Table 5.
	14	23					6 Feb	(1)L.shoulder, scapula	1 3/4 hrs	
L	15	33	4/6	10 Feb	76	77	7 Feb	(1)R.shoulder, Hip	7 hrs	Treatment Table 5.
Q	16	29	5/6	3 Mar	79	78	28 Feb	(1)R.knee	45 min	Treatment Table 5.
	17	26					28 Feb	(1)R.forearm	8 hrs	Treatment Table 6.
R	15	33					10 Feb	(3)Shortness of breath. Postural hypotension, shivering,pain both shoulders,severe skin mottling	20 min	Diver said shortness of breath began at 60' stop during decompression in test dive. Felt very cold. Started taking prostaphlin 24 hrs before dive for paronychia. Treated at 60 FSW for 4 hrs while receiving 3000cc fluids. Decompressed on sat schedule. Breathed air during decompression. Only symptom after surfacing was malaise which disappeared in one week.
M	12	38	5/7	6 Mar	76	72	2 Mar	(1)L.wrist	1 hr	Treatment Table 5. All divers complained of being very cold during the dive.
	18	29						(1)R.shoulder	7 hrs	
	19	29						(1)L.shoulder	1½ hrs	
N	20	27	5/8	7 Mar	73	73	28 Feb	(2)Mild paresthesia L.leg	1½ hrs	Treatment Table 6. Diver very cold and tired.
P	21	30	5/3	14 Mar	83	78	10 Mar	(2)R.retro-occular headache, trouble focusing	2 hrs	Treatment Table 6. Diver reported P_{O_2} between .5 and .6 ATA most of the time because of rig malfunction.

APPENDIX 4

DECOMPRESSION PROFILES FOR A CONSTANT

0.7 ATA P_{O_2} in N_2

All ascent and descent rates are 60 FPM.

Bottom time includes descent time.

Time between stops 10 seconds.

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW) 10	Total Ascent (Min:Sec)
40	360	0:40	No Decompression	0:40
50	30	0:40	2	2:50
	60	0:40	5	5:50
	90	0:40	7	7:50
	120	0:40	10	10:50
	150	0:40	12	12:50
	180	0:40	14	14:50
	210	0:40	16	16:50
	240	0:40	20	20:50
	270	0:40	23	23:50
	300	0:40	25	25:50
	330	0:40	27	27:50

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW) 20	10	Total Ascent (Min:Sec)
60	30	0:40	1	5	7
	60	0:40	3	9	13
	90	0:40	4	14	19
	120	0:40	5	19	25
	150	0:40	7	21	29
	180	0:40	9	28	38
	210	0:40	10	33	44
	240	0:40	11	37	48
	270	0:40	11	44	55
	300	0:40	14	48	63

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW)			Total Ascent (Min:Sec)
			30	20	10	
70	20	0:50		2	4	7:10
	40	0:40	1	4	9	15:10
	60	0:40	1	7	12	21:10
	80	0:40	2	9	17	29:10
	100	0:40	2	11	20	34:10
	120	0:40	3	14	24	42:10
	140	0:40	3	16	30	50:10
	160	0:40	3	18	35	57:10
	170	0:40	4	19	37	61:10

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW) 40	30	20	10	Total Ascent (Min:Sec)
80	10	1:00			2	3	6:20
	20	0:50		2	3	5	11:20
	30	0:50		2	5	8	16:20
	40	0:50		4	6	10	21:20
	50	0:50		4	8	12	25:20
	60	0:50		5	9	16	31:20
	70	0:40	1	6	9	20	37:20
	80	0:40	1	7	12	20	41:40
	90	0:40	1	8	14	20	44:40
90	10	1:00		1	2	3	7:30
	20	0:50	1	2	4	6	14:30

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW)				Total Ascent (Min:Sec)
			40	30	20	10	
90	30	0:50	2	4	5	10	22:30
	40	0:50	2	5	8	12	28:30
	50	0:50	3	6	9	17	36:30
	60	0:50	4	8	9	20	42:30
	70	0:50	4	9	13	20	47:30

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW) 60	50	40	30	20	10	Total Ascent (Min:Sec)
100	10	1:10				2	2	3	8:40
	20	1:00			2	2	5	7	17:40
	30	0:50		1	3	4	7	10	26:40
	40	0:50		1	4	5	9	15	35:40
	50	0:50		2	4	8	9	20	44:40
	55	0:50		2	4	9	11	20	47:40
110	10	1:10			1	2	2	4	11:50
	20	1:00		2	2	4	5	9	23:50
	30	0:50	1	2	4	4	8	12	32:50
	40	0:50	1	3	4	7	10	18	44:50
	45	0:50	1	4	4	9	10	20	49:50

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW) 90	80	70	60	50	40	30	20	10	Total Ascent (Min:Sec)
120	10	1:20						2	2	2	5	13:00
	20	1:00				1	2	2	4	5	10	26:00
	30	1:00				2	3	4	6	9	15	40:00
	40	1:00				3	4	5	9	10	20	53:00
130	10	1:20					1	2	2	3	5	17:10
	20	1:00			1	2	2	4	4	7	10	31:10
	30	1:00			2	2	4	4	8	9	17	47:10
	35	1:00			2	3	4	5	9	10	20	55:10
140	10	1:30					2	2	2	4	5	17:20
	20	1:10			2	2	2	4	4	8	11	35:20
	30	1:00		1	2	3	4	5	9	9	20	55:20

DECOMPRESSION TABLES

0.7 ATA Constant P_{O_2} in N_2

Depth (FSW)	Bottom Time (Min)	Time to First Stop (Min:Sec)	Decompression Stops (FSW) 90	80	70	60	50	40	30	20	10	Total Ascent (Min:Sec)
150	10	1:30				1	2	2	2	4	5	18:30
	20	1:10		1	2	2	3	4	4	9	12	39:30
	30	1:00	1	2	2	4	4	6	9	11	20	61:30

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